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Trombe walls: A review of opportunities and challenges in research and development

Omidreza Saadatian*, K. Sopian, C.H. Lim, Nilofar Asim, M.Y. Sulaiman

Solar Energy Research Institute (SERI). Level 3, Perpustakaan Tun Sri Lanang, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

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ABSTRACT

Green building and sustainable architecture are new techniques for addressing the environmental and energy crises. Trombe walls are regarded as a sustainable architectural technology for heating and ventilation. This article reviews the application of Trombe walls in buildings. The reviews discuss the characteristics of Trombe walls, including Trombe-wall configurations, and Trombe-wall technology. The advantages and disadvantages of this sustainable architectural technology have been highlighted, and future research questions have been identified.

Contents

1. Introduction

Fossil energy is an essential component of daily life whose environmental impact and fast-increasing price are two important concerns in the millennium [1]. For instance, two price

* Corresponding author. Tel.: +60 172075459; fax: +60 38921 4593.
E-mail address: omid.saadatian@gmail.com (O. Saadatian).

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increases, which occurred from 1973 to 1983 and from 1998 to 2008, affected the social and economic aspects of many lives [2]. Moreover, the depletion of natural resources generated interest in renewable energy sources, such as the sun [3], wind [4], biomass [5], waves [6], rain [7], tides [8] and geothermal heat [9–11].

Solar energy plays an important role for numerous people in different walks of life. Solar energy can be used in remote and undeveloped areas to meet the requirements of schools, clinics and other buildings [12]. Building accounts for 33% of the world's total greenhouse-gas emissions [13]. In the building industry, the significance of solar energy is more obvious when the role of architecture, the use of renewable energy, and climatic design are taken into account. These factors are the main guidelines for energy conservation in the building sector [14–16].

Passive solar techniques can reduce annual heating demand up to 25% [17]. Various architectural devices, such as solar chimneys [18], solar roofs [19], Trombe walls [20–22], etc., are used in construction. These devices diminish environmental degradation and reduce greenhouse gas emissions [23,24]. Trombe walls, which are also known as storage walls and solar heating walls (SHW) [25,26], reduce a building's energy consumption up to 30% [27]. A Trombe wall is an important green architectural feature that aides the ventilation, heating, and surprisingly, cooling of buildings.

This architectural element is important enough to inspire the managers of Zion National Park in the USA to integrate it into the park's new Visitor Centres [28]. Zion National Park is located in the Renewable Energy Laboratory's (NREL's) National Wind Technology Centre in the USA. This paper examines this green technology by reviewing research findings and aims to provide a comprehensive and critical source of information. We hope that this source of information is useful to individuals in the field of passive design.

2. Configuration of Trombe walls

The idea that underlies Trombe walls is using solar energy to heat, ventilate and provide thermal comfort in buildings in various climatic regions [29]. Trombe walls function by absorbing solar rays and converting their energy. A Trombe wall stores energy during peak-use periods and supplies energy when a building's occupants require it [30,31]. Different configurations are used to adapt Trombe walls to various climates, purposes and seasons (see Fig. 1).

In this section, nine different types of Trombe wall will be discussed: (1) a classic and modified Trombe wall; (2) a zigzag Trombe wall; (3) a solar water wall; (4) a solar transwall; (5) a solar hybrid wall; (6) A Trombe wall with phase-change material; (7) a composite Trombe wall; (8) a fluidised Trombe wall; and (9) a photovoltaic Trombe wall.

2.1. Classic Trombe wall

A classic or standard Trombe wall is a simple Trombe wall in which glass and an air space separate the wall from the outdoor environment [32–36]. The inventor of this type of Trombe wall was Edward Morse, an American engineer who patented his design in 1881. However, the classic Trombe wall has been popularised by Felix Trombe and Jacque Michel, a French engineer and a French architect, respectively [33,37]. Therefore, this wall is known as a Trombe wall [33,37].

Hatamipour and Abedi have claimed that the idea of Trombe walls is the same as that of the gangway in the vernacular architecture of the Persian Gulf [38]. This gangway is a corridor that separates the main entry of the rooms from the main hall and has windows on the sides. The walls of the gangway store heat, and the corridor resembles the air gap between the glazing and the heat storage wall of the Trombe wall (see Fig. 2). The Trombe wall absorbs solar energy and releases it to provide thermal comfort. For optimal performance, this wall is usually positioned facing south (see Fig. 3).

The design of a classic Trombe wall is based on using materials with high heat-storage capacity. These materials include bricks, concrete, stone and adobe. The external surface of the wall is coloured black to increase the absorption rate [39–41]. Moreover, the surface of the Trombe wall is glazed. An air gap is left between the glass and wall [33,37].

Fig. 2. A gangway with windows in its sides resembles a solar wall [38].

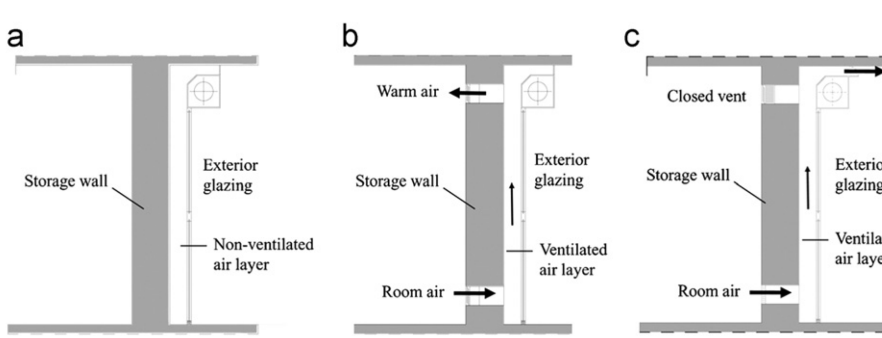

Fig. 1. Various configurations of a solar wall: (a) without ventilation; (b) winter mode with air thermo-circulation; (c) summer mode with cross ventilation [32].

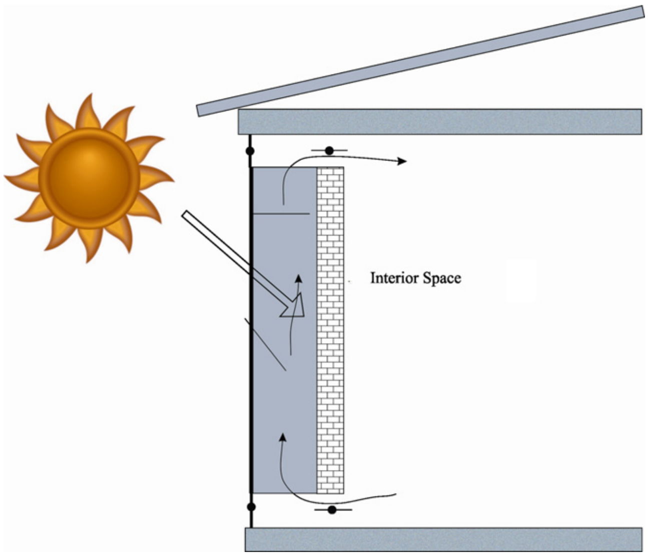

Fig. 3. A simple diagram of a solar wall.

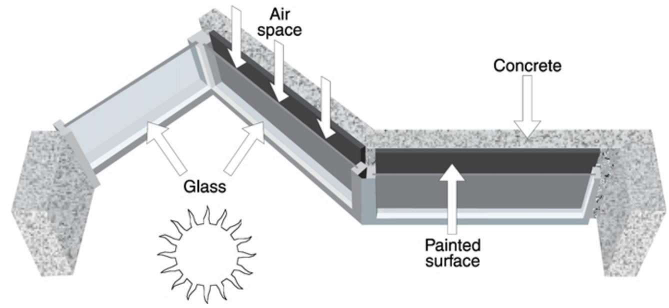

Fig. 4. A zigzag solar wall [47].

Fig. 5. A project in North Carolina uses a zigzag solar wall.

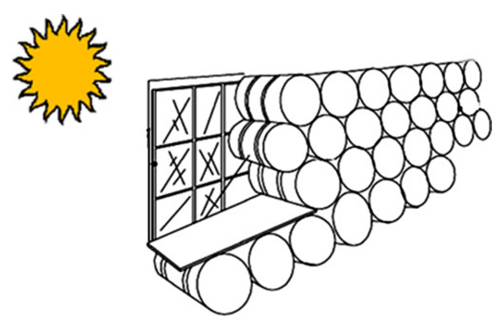

Fig. 6. A sketch of water wall.

The wall absorbs diffused and direct solar radiation during the day and transfers the heat to the interior of the thick storage mass wall by convection or conduction at night [33]. The gap between the glass and the wall normally ranges from 3 cm to 6 cm [42]. The heat that is stored in the thermal mass is released gradually. This heat transmission occurs through radiation and convection to increase thermal comfort for the building's occupants (see Fig. 2). Convection produces the air flow as a result of the solar buoyancy effect [43].

In addition, classic Trombe walls can be modified into different shapes. The commercial modified Trombe wall (MTW) is a Trombe wall that is lined with gypsum board. This Trombe wall has a masonry outer layer and gypsum board inner layer. There is an air gap between the layers. The MTW has other components that can be found in a classic Trombe wall [44]. According to Khedari et al., this type of Trombe wall induces natural ventilation well [45]. A dark-coloured 2 m^2 MTW with a 14 cm air gap can induce 20–90 m^3/h air ventilation [45].

2.2. Zigzag Trombe wall

Another type of Trombe wall is a zigzag Trombe wall. This Trombe wall is designed to reduce the excessive heat gain and glare of sunny days. The wall comprises three sections. One section faces south. However, the two other sections are angled inward forming a V-shaped wall [27,46]. The section that faces southeast has a window that provides heat and light in the morning cold when immediate heating is required [27,46]. Opposite the V shape is a classic Trombe wall, which stores heat for redistribution in the cold night hours (see Fig. 4).

The zigzag design also incorporates an exterior overhang to avoid overheating during hot summer days. A prototype of this type of Trombe wall with five V-shaped sections has been constructed at the visitor centre of NREL [47,48]. In addition, a 1200 m^2 residential structure has been built near Asheville, North Carolina, using the same system [49] (see Fig. 5).

2.3. Water Trombe wall

Another type of Trombe wall is the water wall, which works on the same principle as the classic Trombe wall. However, instead of using masonry for heat storage, a container of water in the shape of a wall is employed [50,51] (see Fig. 6). Because water performs better than masonry in indirect heat gain, this type of wall has attracted many designers interested in passive heating. The reason for this improved performance is that the water's surface temperature does not rise as high as that of the masonry. Therefore, less heat is reflected back through the glazing [27].

This type of wall has glazing in front of the water container, which enables the sun's rays to penetrate. The water distributes the heat by convection, and the water Trombe wall transfers the heat into the room through radiation [33]. In this type of Trombe wall, the exterior of the wall is darkened to increase the absorption of solar radiation. In certain types of Trombe wall, an insulated film or a very thin concrete wall is attached to the Trombe wall's interior side. This insulated film increases the wall's efficiency. Because the specific heat of water (C) is higher than that of other types of building material, such as concrete, bricks, adobe, and stone, water stores more heat than the other materials. Similarly, because water convects, the transfer of heat to the interior space occurs faster than with classic Trombe walls. In harsh cold climates, the glass layer should be insulated. Otherwise, the loss of heat from the warm wall to the outside would be significant [39].

The water Trombe wall can function for both cooling and heating, which is a distinctive architectural feature. However, containing liquids such as water is much more difficult than containing solid materials such as masonry. Therefore, this type of Trombe wall has not been appreciated as much as classic Trombe walls by building stakeholders [52].

In Oregon, Adams et al. performed an experimental study on the effects of the thickness of a water Trombe wall on the wall's efficiency [53]. In a controlled environment, three different wall thicknesses (3 in., 6 in., and 9 in.) were examined [53]. The study reveals that 9-in. and 6-in. water walls perform better than the 3-in. water wall [53] and concludes that a thicker wall helps to maintain a cooler interior temperature during hot weather and a warmer interior temperature when the outside temperature is low [53].

2.4. Solar transwall

A transwall is another type of Trombe wall. A transwall is a transparent modular water wall [54]. A transwall plays an aesthetic role by providing visual access to a building's interior. In addition, it provides thermal gain from solar radiation. This wall is built on a metal frame that holds a water container constructed from glass walls and a semi-transparent absorbing plate that is positioned between the walls (see Fig. 7).

The semi-transparent plate absorbs (4/5) of the solar energy and transmits the rest of the energy inside. Therefore, this type of wall uses the direct and indirect gain systems and is suitable for locations where daytime temperature is high [12]. Convective heat transfer in a transwall lessens the efficiency of this type of wall. However, installing transparent baffles overcomes this deficiency. To increase the viscosity of the water and to prevent microorganisms from growing in the water, gelling and bio-inhibiting agents should be added to the water [12].

2.5. Solar hybrid wall

The Trombe wall is famous for its heating effects during winter and is designed for cold climates. However, Spanish scholars have presented a hybrid prototype Trombe wall: the ceramic evaporative cooling wall. The wall functions as a classic solar wall during winter and provides cooling in summer [55] (see Fig. 8).

The solar hybrid wall prototype uses the design of a standard Trombe wall. However, the wall employs an external thermal insulation blind during summer to avoid any direct solar gain [55]. Moreover, a special type of ceramic is used in the interior wall known as porous ceramic, which absorbs a significant amount of water. In hot weather, the ceramic is wetted by a water nozzle installed at the roof over the gap between the glass and the wall, which causes the gap to function as a cooling chamber due to the evaporative cooling phenomenon [55].

2.6. Trombe wall with phase-change material

This Trombe wall is a new type, which uses a phase-change material such as phase eutectic salts or salt hydrates to enhance efficiency. A thick, massive wall, which is heavy and increases a building's dead load, is considered a problem by structural engineers. This problem is addressed through the use of a new type of material known as phase-change material [50,56,57]. These phase-change materials store more energy in a smaller volume and in materials than are lighter than normal building materials [57,58]. According to a numerical study by Bourdeau,

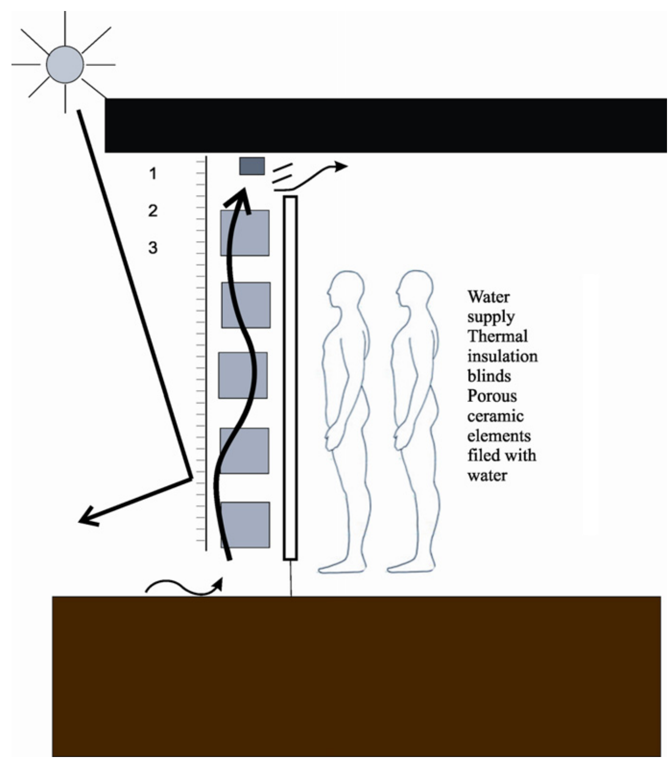

Fig. 8. Solar ceramic evaporative cooling wall [55].

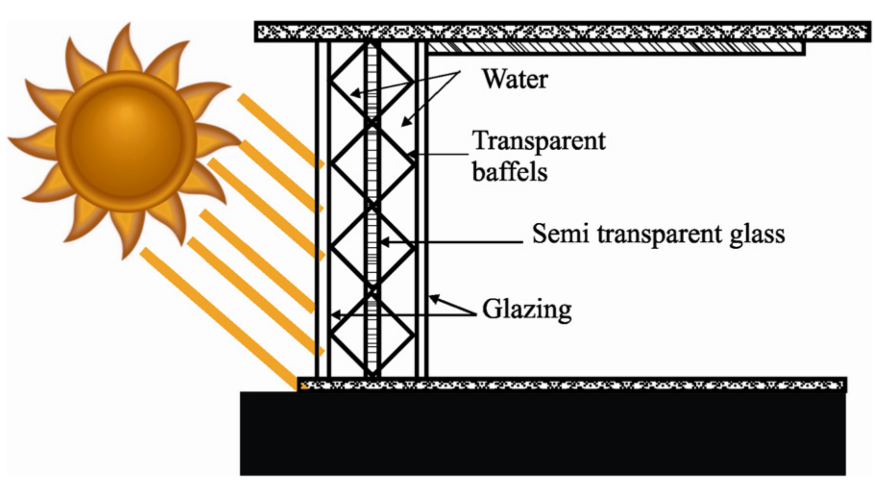

Fig. 7. Details of a Transwall.

a 15 cm concrete wall can be replaced by a 3.5 cm wall of phase-change material and perform similarly [59].

A group of Japanese scientists under Onishi undertook a computational fluid-dynamics simulation of the thermal behaviour of a room with phase change-material Trombe walls. The group analysed three phase-change materials and established that use of phase-change materials in Trombe walls is valuable for reducing energy consumption in buildings [60].

Different phase-change materials affect the performance of Trombe walls differently. For instance, in a computerised dynamic simulation that was conducted by Khalifa and Abbas in Baghdad, Iraq, for a south-facing Trombe wall, various phase-change materials showed different reactions (see Table 1). Khalifa and Abbas examined paraffin wax and hydrated salt encapsulated in copper capsules with a length-to-diameter ratio of 0.76. The researchers realised that an 8 cm thick hydrated salt storage wall is more efficient than a 20 cm thick concrete or a 8 cm thick hydrated salt storage wall [61]. Additionally, an 8 cm thick hydrated salt storage wall maintains temperature better than a 5 cm thick paraffin wax wall [61] (see Table 1).

Bourdeau performed another experimental study on Trombe walls with phase-change materials. The Trombe wall was constructed from a polyethylene container positioned on a wooden shelf and double glazed [59]. The results indicated that latent heat storage becomes saturated during the operation and a Trombe wall with latent heat storage is more efficient than a concrete wall [59].

In France, Zalewski et al. conducted an experimental study on a small-scale Trombe wall. In their study, a concrete storage wall was replaced by a new wall that contained hydrated salt to examine the walls' efficiency [58]. The results of the study demonstrated that the hydrated salt can release the solar gains with a time lag of two hours and 40 min [58]. This time lag is considered a negative phenomenon in winter if the wall is designed for a dwelling and insulated to take advantage of gains at the end of the day. However, such a wall can be considered advantageous when used in structures that are occupied during the day, such as shopping malls, clinics, universities and schools in winter [58].

2.7. Composite Trombe wall

The composite Trombe wall, which is also known as the Trombe–Michel wall [62,63], is another type of Trombe wall, which consists of several different layers. These layers include a semi-transparent cover, a mass heating wall, a closed cavity, a ventilated air cavity and an insulating panel (see Fig. 9). Composite Trombe walls are considered a remedy for two deficiencies of Trombe walls: (1) heat loss during cloudy winter days and (2) undesired heat inputs during hot weather [64].

The composite Trombe wall functions as follows. The first layer, which is transparent, dispatches the majority of the gained solar beams. Consequently, the storage wall absorbs a portion of the gained solar energy and heats up. The mass wall stores and transmits part of the absorbed energy into the building's interior. This energy transfers into the room by convection through the ventilated channel. In addition, a small portion of the energy is transmitted by conduction from the wall into the room. These free solar gains must be distinguished from direct solar gains.

The advantages of composite Trombe walls are as follows: (1) Users can control the rate of heating by controlling the airflow into the ventilated channel. (2) The composite Trombe wall's thermal resistance is extremely high because the walls and ventilated channel are insulated. One disadvantage of a composite Trombe wall is that the wall requires a mechanism to prevent reverse thermo-circulation, which occurs when the storage wall becomes colder than the ambient air of the building's internal space [58].

This problem can be solved by inserting a plastic film in the vent, which functions as a thermal diode [65]. Shen et al., a group of scholars based in France, compared the classic Trombe wall with the composite Trombe wall using TRNSYS software and validation by experiential testing to analyse the walls' efficiencies [66,67]. The results demonstrated that the composite Trombe wall performs better during winter, particularly in cold or cloudy climates [66].

2.8. Fluidised Trombe wall

Another type of Trombe wall is the fluidised Trombe wall, which is based on the classic Trombe wall but in which the gap between the Trombe wall and glazing is filled with a highly absorbent, low-density fluid [68–70].

A fan transfers the solar energy gained by the absorptive fluid by moving the heated air to the room. Two filters, which are located at the top and bottom of the air channel, prevent the fluidised particles from entering the room [68]. A study conducted by a group of Turkish scholars compares the classic Trombe wall with the fluidised Trombe wall. The group used theoretical and experimental studies on fluidised beds and a finite-difference procedure to solve the governing equations using air as the fluid. The results indicated that fluidised Trombe walls are far more efficient than classical Trombe walls because the

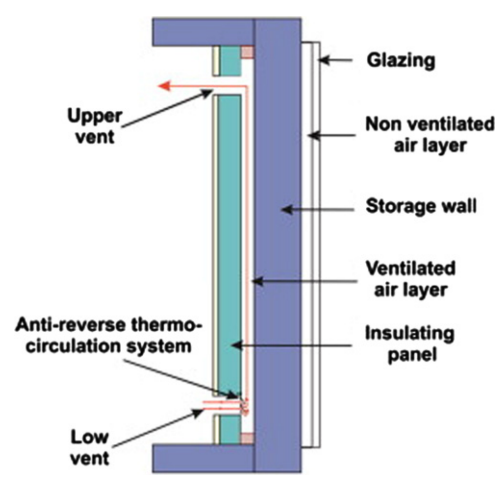

Fig. 9. A composite solar wall [58].

Table 1
A comparison of concrete, hydrated salt and paraffin wax.

Solar wall attributes	Concrete	Hydrated salt	Paraffin wax
Temperature of room (°C)	15–25	18–22	15–25
Variation of temperature in the mass wall during night hours (°C)	1–3	4–6	3–7
Variation of temperature in the mass wall during day hours (°C)	7–15	10–18	10–22
Thickness of thermal storage wall (cm)	20	8	5

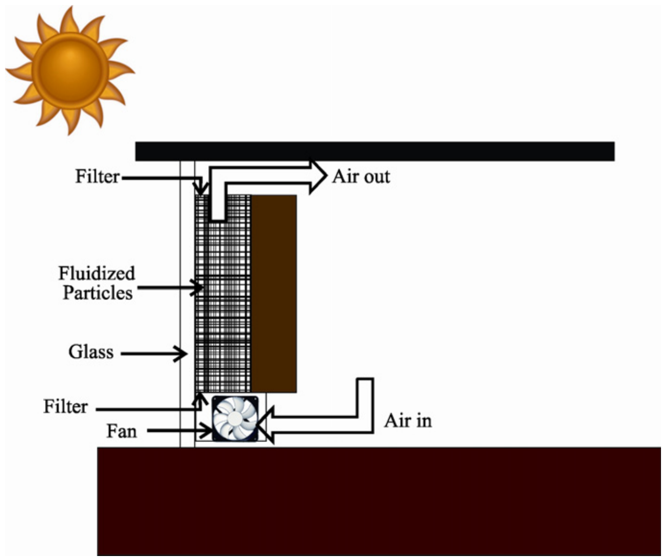

Fig. 10. Different parts of the fluidised wall [68].

heat-transfer fluid is in direct contact with the particles [70] (see Fig. 10).

2.9. Photovoltaic (PV) Trombe wall

A new invention is the PV-Trombe wall, in which the front side of the glazing is composed of photovoltaic panels that simultaneously convert solar radiation into heat [71] (see Figs. 11 and 12). The PV-Trombe wall is considered an aesthetic approach in designing Trombe walls. This wall does not have the unsightliness of a normal Trombe wall, in which glass covers a black mass wall. The dark blue solar cells can add beauty to a building and increase the building's appeal [71,72]. With the PV-Trombe wall, the cool air of the room is drawn in from the lower vent, absorbs the PV heat, becomes hot and travels inside the room before exiting through the upper vent. Absorbing PV heat increases the efficiency of PV panels because the panels function better when they are cool [73,74].

The PV-Trombe wall uses a PV panel, which hinders the penetration of solar rays into the air space between the walls and glazing [75]. Therefore, the efficiency of the Trombe wall is reduced in terms of heat gain. However, this type of Trombe wall generates electricity, which is considered a benefit. Therefore, the question arises of how much the efficiency of classic Trombe walls will be changed when a PV panel covers the glazing. To answer the question, Sun et al. performed an experiment and a computer simulation to measure the internal temperature of a building. The building was equipped with south-facing windows and a 0.83 m wide and 2.6 m tall PV panel installed on a Trombe wall. Developing a dynamic numerical model, Sun et al., simulated all of the building's components. The study revealed that installing PV panels over the glazing reduces the thermal performance of the Trombe wall up to 17% [71]. This reduction is due to the obstructed penetration of the sun's rays into the mass wall [71].

Another group of scholars studied the use of the PV-Trombe wall, the wall's optimal width and the wall's optimal area of winter air vents [76]. Additionally, the group investigated the effects of insulation and a shading curtain on winter heating and summer cooling [76]. The results revealed that insulation increases the indoor temperature by 2.36 °C in cold weather and decreases the indoor temperature by 2.47 °C in hot weather [76]. Moreover, curtain shading decreases the internal temperature by

Fig. 11. A PV-Trombe wall and a window [71].

2.00 °C in hot weather and may decrease the electrical performance rate less than 2% [76].

3. Efficiency analyses

Trombe walls have various accessories that help increase efficiency. Important accessories include vents [77], fans [78,79], and insulation [80]. Certain intrinsic Trombe wall attributes contribute to the wall's efficiency. Size, thickness, colour, wall materials, coating materials, and glazing specifications are among the important Trombe wall attributes that affect the wall's efficiency. In the following sections, these accessories and attributes will be discussed.

3.1. Vent effects

Classic Trombe walls could be categorised in two types: vented and unvented [81] (see Fig. 1). For vented Trombe walls, two thermocirculation vents are installed at the top and bottom of the wall to assist heat circulation. These vents are designed to control the heat loss. The heat loss occurs in the air space between the glazing and wall through convection, conduction or radiation back to the atmosphere. The higher the temperature of the air space, the greater is the heat loss. Vents are installed at the wall's top and bottom to reduce the heat loss. As the air in the air space becomes warm and lighter, it enters the room through the upper vent, and cool air replaces it through the lower vent [33].

The closing or opening of vents changes the heat-transfer coefficients between the air in the gap and the wall and glazing. When the vents are closed, the heat-transfer coefficient should be measured for optimisation. For measurement, the amount of infrared radiation and the natural convection exchange between grey-surface problems for vertical collectors should be determined [82]. However, when the vents are open, a mathematical equation is used to calculate the transfer coefficient.

For vented Trombe walls, the vents are an important control mechanism, which can assist buildings in heating and cooling [25]. The efficiency of vented and unvented Trombe walls has long been regarded as an important topic in passive-energy research. For instance, Balcomb and McFarland studied the performance of

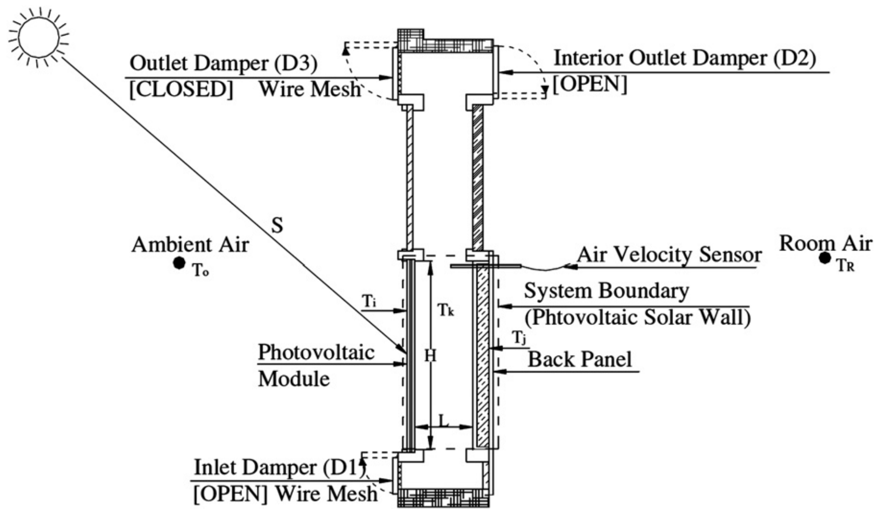

Fig. 12. Details of PV Trombe wall [75].

Trombe walls with thermocirculation vents and unvented Trombe walls in nine different climates of the USA. Their study revealed that vents produce a reverse flow during the night and reduce the efficiency greatly under certain circumstances [83].

Balcomb and McFarland proposed using dampers to control the vents to prevent reverse flow. Their results revealed that the use of controlled vents does not significantly affect the performance of Trombe walls in mild climates [83]. They concluded that vented Trombe walls function 10–20% more efficiently in severe climates, such as that of Boston [83]. Furthermore, the research team simulated a thermostatically controlled vented system in which dampers were closed when the internal temperature of the building exceeds 24 °C [83]. This method was found to prevent overheating [83].

A simulation study using Energy Plus software was conducted by a group of Portuguese scientists in three different climatic regions of Portugal. The study aimed to determine the effect of vents on Trombe-wall efficiency [84]. The study's results confirmed the findings of Balcomb and McFarland [83].

In designing a Trombe wall, vent size is an important parameter and depends on the solar saving fraction (SSF) [85]. Additionally, external vents, which can be installed in the exterior part of Trombe walls, facilitate the air circulation [86]. This circulation enables better ventilation and cools the air space between the glazing and main wall during summer [86].

3.2. Fan effects

The feasibility of using fans to assist the circulation of heat through the vents is questionable [85]. A thermal network computer simulation was performed by Sebald et al., on a Trombe wall with a thermostatically controlled fan. The thermostatically controlled fan started when the outside wall temperature exceeded 29 °C. The results revealed that the fan's performance depends on parameters such as the wall's thickness and climate [79]. For instance, a fan can improve the efficiency of a 37 m^2 room with a Trombe wall by 22% in Albuquerque, 20% in Santa Barbara and 7% in Madison [79].

At the University of California, Sebald and Phillips performed another simulation study on the efficiency of a fan-equipped Trombe wall. In the study, the fan started when the room required heating and the temperature of the gap between the glazing and wall exceeded the room temperature by more than 10 °C [87]. The results indicated that a fan improves the performance of Trombe walls by up to 8%.

Another simulation, which was validated by a field test, was conducted by Jie et al., on the efficiency of a PV-Trombe wall with and without a fan at the University of Science and Technology of China (see Fig. 13). The study determined that the fan reduces the internal temperature by 0.5 °C and reduces the temperature of the PV cells by 1.28 °C [72]. In addition, the study observed that a fan can reduce the temperature of PV cells by 1.28 °C between 7:00 and 17:00, which causes the PV cells to function more efficiently [72].

However, based on the review performed by the authors, the majority of the research conducted in this area relies exclusively on computer modelling, in which questions of validity might not have been fully addressed.

3.3. Size effects

The size of Trombe walls or, more precisely, the ratio of the Trombe wall's area to the total wall area has been proposed as a parameter of Trombe-wall efficiency [82,88]. Based on a study undertaken by Jaber et al., on a typical Jordanian house, which was modified using a Trombe wall, the ratio of Trombe wall area to the wall area (α) has a direct effect on thermal efficiency [82]. If (α)=20%, the Trombe wall can save up to 22.3% of heating auxiliary energy annually [82]. However, if (α)=37%, the Trombe wall will be able to save up to 32.1% of heating auxiliary energy annually [82]. For (α) larger than 37%, the amount of savings will be almost negligible (see Fig. 14).

In other words, in Trombe-wall design, the optimal Trombe wall area ratio or (α) is 37% [82].

3.4. Thickness and colour effects

Generally, the optimal thickness of a Trombe wall is related to latitude, climate and heat loss [27]. The thickness of the mass is one parameter that contributes to the effectiveness of Trombe walls. For example, with concrete, there is a lag of 120 min to 150 min for heat delivery from outside to inside for each 10 cm [33]. Insufficient wall thickness results in excessive interior temperature swings, while increasing the thickness will increase costs. With a very thick Trombe wall, the heat requires too long to reach the interior, which causes thermal discomfort for the building occupants [48]. In this regard, in India, Agrawal and Tiwari have proposed a 30–40 cm thick concrete Trombe wall for optimal results [33].

With respect to the effect of colour, in Turkey, Ozbalata and Kartal employed the unutilisability method to determine the

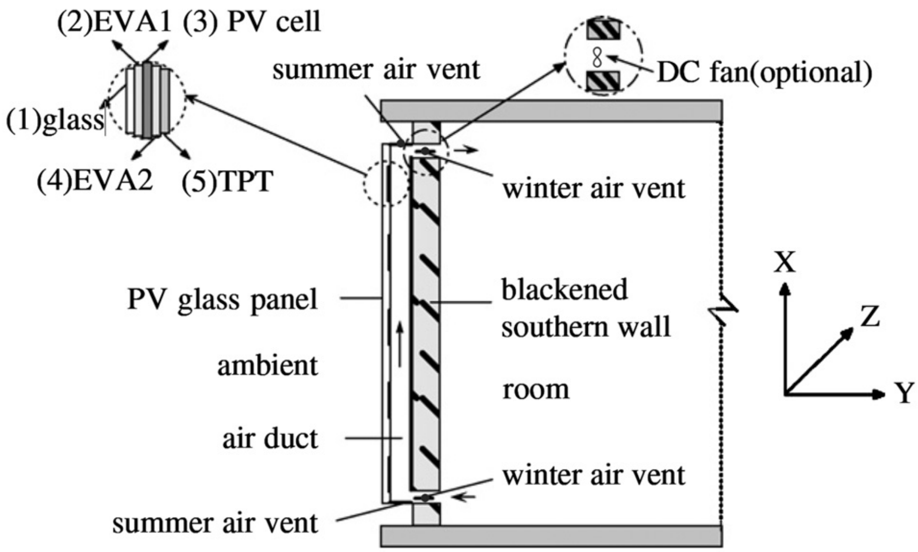

Fig. 13. PV-solar wall with DC fan [72].

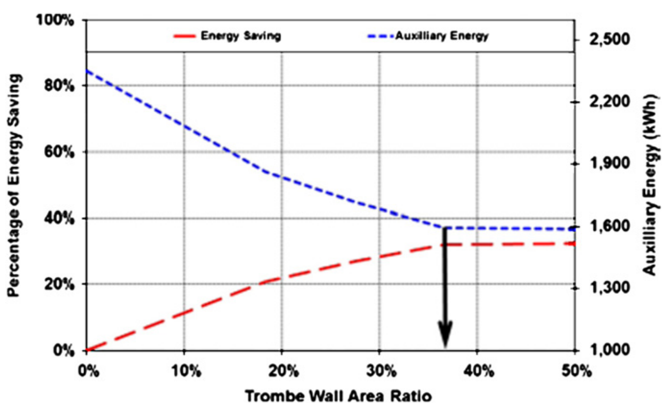

Fig. 14. Energy savings based on the size of the solar wall.

effects of three colours on the performance of Trombe walls. The colours included dark, natural and light [89]. Brick wall, concrete wall, and autoclaved aerated concrete wall were used as the main material of the solar mass. The study revealed that the annual heat gain varied from 26.9% to 9.7% for concrete, 20.5% to 7.1% for brick and 13.0% to 4.3% for aerated concrete according to surface colour (see Table 2; [89]).

3.5. Insulation effects

A classic Trombe wall possesses low thermal resistance and loses a large amount of heat at night [66,90]. In hot weather and particularly in well-insulated buildings, Trombe walls might function as a source of undesired heat gain and overheating due to reverse heat transfer [32]. To prevent reverse heat transfer, Trombe walls should be properly insulated. Fifteen years ago, a UK scholar studied this problem with an experimental validated CFD programme [91]. The study suggested that proper insulation is necessary for maximising the ventilation rate of a building integrated with Trombe walls during summer [91]. Additionally, the study proposed that the interior of Trombe walls should be insulated [91].

A group of researchers in Canada undertook a theoretical study on the use of insulation in a composite Trombe wall to examine overall insulated Trombe-wall efficiency [92]. The composite

Table 2
Effects of colours on the performance of the solar wall [56].

Solar wall colour	Annual solar heat gain %		
	Reinforced concrete	Brick	Autoclaved Aerated concrete
Dark colour	26.9	20.5	13.0
Natural colour	20.2	16.4	7.9
Light colour	9.7	7.1	4.3

system consisted of a glass panel, a mass wall, and an insulated wall. There were vents between the mass and insulated walls. The study revealed that an insulated composite Trombe wall can perform much better than the classic Trombe wall in cold and cloudy weather [92]. Additionally, the study concluded that use of insulation and a composite wall can enable a reduction in the thickness of the solar mass wall. This combination of wall materials is appealing to structural engineers, who usually desire light buildings [92].

According to Ji et al., thermal insulation in both winter and summer improves the efficiency of a PV-Trombe wall [76]. Another empirical study was conducted on a residential building in Alcona, central Italy [32]. The study used a simulation that employed Energy Plus software [32]. One objective of the study was to analyse the effects of insulation in the Trombe wall. The simulation results for a normal Trombe wall and a super-insulated Trombe wall were compared. The results showed that the seasonal heating-energy demand for a normal Trombe wall was 58.33 (kW h/m^2) [32]. However, the same parameter for a super-insulated Trombe wall was 16.21 (kW h/m^2), which is approximately 28% of the result for the former wall. For cooling, the results were the opposite. For a normal Trombe wall, the amount of energy required was approximately 9.19 (kW h/m^2) and for a super-insulated Trombe wall approximately 23.31 (kW h/m^2) [32].

Although the result showed that insulation improves efficiency in winter and increases energy consumption in summer, the overall efficiency of the insulated system is much higher. The total demand for seasonal heating and cooling of a normal Trombe wall is approximately 62.88 (kW h/m^2). An insulated Trombe wall requires approximately 29.58 (kW h/m^2), which is approximately 47% of the energy requirement of the normal wall [32]. Nevertheless, Zalewski believes that the efficiency of insulation

depends on many variables [93]. Zalewski suggested that the usefulness of insulation should be investigated separately according to Trombe-wall type and location [93].

Another numerical study, which addressed the same concern, was undertaken in Xining, China, on an improved type of composite Trombe wall with insulated internal and cavity walls [94]. The study aimed to compare insulated with non-insulated composite Trombe walls. The research revealed that this manner of insulation increases the efficiency of a composite Trombe wall by 56% [94].

3.6. Wall-material effects

The type of material used to construct a Trombe wall contributes importantly to the efficiency of the wall's heat storage, convection and conduction. A group of Algerian scholars used computational fluid dynamics (CFD) to study a room located in Bechar, Algeria [25]. They concluded that the mass wall is the most crucial part of a classic Trombe wall [25]. Similarly, Zalewski et al. found that a Trombe wall's material is the key determinant of a Trombe wall's storage capacity [58]. Knowles conducted an experimental study by replacing a paraffin–metal mixture wall with a concrete wall. The results revealed that a concrete wall reduces storage mass by 90% and increases system efficiency more than 20% [95]. Increasing the weight and volume of Trombe walls increases the storage capacity of the walls. However, this increase in dead load is not desirable for architects and structural engineers.

A study by Hassanian et al. of Egypt's Suez-Canal University examined the effects of various adobe materials on the efficiency of Trombe walls [96]. In experimental tests, the study found that various adobe materials result in different efficiency in Trombe walls and can greatly affect the performance of Trombe walls.

The materials used to coat the mass wall are considered another significant Trombe-wall component. Therefore, the study of the effects of coating materials on the overall performance of Trombe walls is important. To address this issue, a group of scholars from the University of Nigeria investigated the effects of a range of coating absorption values on the efficiency of a given Trombe wall [97]. The numerical study revealed that high-absorption coating materials improve a Trombe wall's storage capacity [97]. Furthermore, the study suggested that the optimal heat-absorption film should be carefully designed to avoid overheating [97]. Additionally, the study recommended a cost-benefit analysis of expensive coating materials. According to the study, such analysis should be conducted for any project individually [97]. A similar study was also conducted by Nwosu for the equatorial region to analyse the heat-transfer balance across the Trombe wall [98]. The study found that highly absorptive coating materials improve the wall's storage capacity and enhance system efficiency [98].

3.7. Glazing effects

The use of proper glazing materials is another important subject in Trombe-wall design. In glazing, not only the material is important. The thickness and the number of the glazing layers are also relevant factors [32]. Normally, glazing is either single or double. According to Stazi et al. in Italy, double glazing improves Trombe-wall performance [32]. In Canada, Richman and Pressnail introduced a new type of glazing, which uses a low-*e* coating film sprayed over spandrel glass. The glazing increases the efficiency of Trombe walls by reducing radiation [99].

A simulation conducted by Zalewski et al. in Trappes (longitude: 2°01′, latitude: 48°46′) and Carpentras (longitude: 5°03′, latitude: 44°08′) studied the effects of glazing materials on Trombe-wall performance. The results revealed that glazing significantly contributes to the efficiency of the Trombe wall [93]. The study showed that use of low-emittance double-glazing increases the collected energy. The amount of this increase was 242% in non-ventilated Trombe walls, 193% in classic Trombe walls, 188% in insulated Trombe walls, and 217% in composite Trombe walls (see Fig. 15) [93]. Additionally, the study revealed that the effects of glazing materials on the efficiency of Trombe walls depend on the longitude and latitude of the wall's location. For this reason, Trappes showed more significant changes compared with Carpentras (see Fig. 16) [93].

3.8. Advantages and disadvantage of Trombe walls

Trombe walls produce large temperature variation in a building's materials. However, Trombe walls cause insignificant temperature variation in heated spaces [39]. A Tunisian study indicates that Trombe walls significantly affect the thermal comfort of occupants [100]. Trombe walls not only provide thermal comfort in the spaces connected to the Trombe wall. They also provide thermal comfort in adjacent spaces [100]. A Trombe wall can reduce a building's energy consumption by 30% [42] and decrease the moisture and humidity of interior spaces in humid regions [101]. In addition to being environmentally friendly, Trombe walls can enhance thermal comfort and save energy even in arid and desert areas [102].

Trombe walls display highly complex behaviour because their operation involves different coupled heat-transfer modes and depends on certain meteorological variables [67]. Trombe walls suffer from four shortcomings.

(1) Trombe walls have low thermal resistance. During the night or prolonged cloudy periods, the heat flux is transferred from the inside to the outside of a building [66,103]. (2) Trombe walls suffer from an inverse thermo-siphon phenomenon. This phenomenon occurs when the mass wall has a lower temperature than room temperature, particularly during the night in the cold season when reversing the air circulation through the vents chills

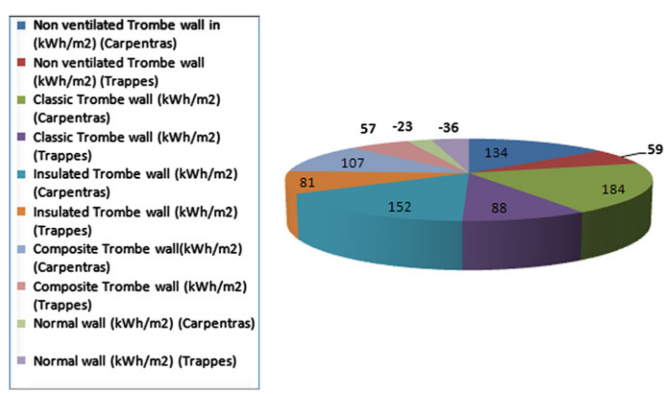

Fig. 15. Collected Energy per m^2 in standard double glazing [93].

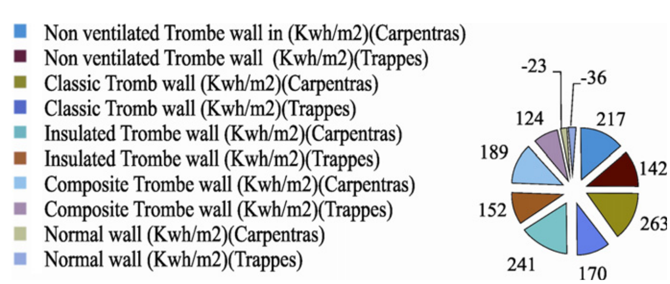

Fig. 16. Collected Energy per m^2 in low-emittance double glazing [93].

the room even more [103,104]. (3) In Trombe walls, heat transfer always proceeds uncertainly. The amount of heat gained is unpredictable due to changes in solar intensity [103,104]. (4). Trombe walls are not sufficiently beautiful, and the aesthetic value of the walls is questionable [72,103].

Simple techniques can control the performance of this system and address some of the shortcomings. These techniques include installing an adjustable curtain between the glazing and wall to regulate the amount of gained energy [105]. Proper glazing insulation, low-e coating, and ultraviolet filters are suggested remedies [106]. Moreover, using an overhang or adjustable shutters are other means to improve the performance of Trombe walls [106].

3.9. Economic perspective

Like any other building element, a Trombe wall is a matter of costs and benefits [107]. For Trombe walls, the additional expense to the client represents a cost, and the amount of energy conservation and Co_2 reduction are benefits. Based on an experimental study conducted in a three-story house with a Trombe-wall basement in Andorra, a Trombe wall can provide approximately 20% of a house's heating demand [108]. Additionally, a Trombe wall can produce large long-term economic benefits for owners [108].

An experimental study by Yimaz and Kundaksi was conducted on an existing building in Istanbul that was retrofitted with a classic Trombe wall to investigate the economic benefit. The study found that Trombe walls generate a large savings in energy consumption in an average Turkish apartment [109]. An Indian simulation study using TRNSYS building simulation software examined the same subject for a honey-storage building. The study found that Trombe walls save up to 3312 kW h/year [110]. Moreover, Trombe walls reduce annual CO_2 emissions by approximately 33 t for a typical Indian honey-storage building [110]. The study concluded that retrofitting such buildings is economically viable because the payback period is only seven months [110].

Jaber et al. also conducted a study on the economic aspect of Trombe walls by using the life cycle cost (LCC) technique on a typical Jordanian house. The house was modified with Trombe walls. The study assumed a 30-year life span for the Trombe walls, an 8.9% inflation rate for fuel, a 6.25% interest rate, and a "present factor worth" (PFW) of 44.96 [82]. The assumed efficiency rate was 65%, and the maintenance factor of the capital investment was 15% [82]. The study concluded that 37% of the total cost can be saved by using this system [82]. The results demonstrated that the LCC of houses without Trombe walls was approximately 49,259 Euros [82]. Nevertheless, in the case study, the use of Trombe walls saved 1169 Euros [82]. Moreover, the break-even point was reached at the Trombe wall ratio of 37%, which required an additional investment of only 1260 Euros (see Fig. 17).

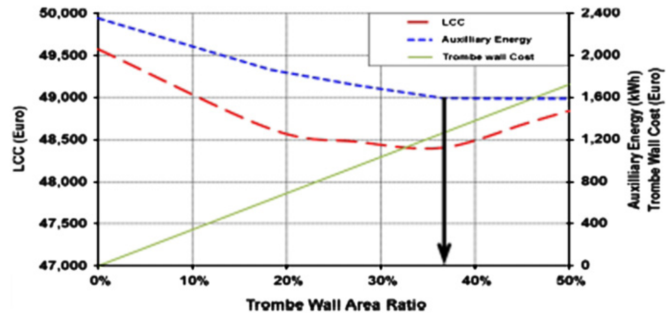

Fig. 17. Economic analyses of a solar wall [82].

4. Summary

Trombe walls are proven to be a suitable passive-energy solution to current environmental and energy crises. Various Trombe-wall configurations exist. These configurations range from those that incorporate new elements into a classic Trombe wall to those that employ modified components Trombe-wall components. Using different configurations, a variety of Trombe walls can be produced. Nine types of Trombe wall are cited most frequently by scientists: classic Trombe walls, zigzag Trombe walls, water Trombe walls, solar transwalls, solar hybrid walls, Trombe walls with phase-change material, composite Trombe walls, fluidised Trombe walls, and PV-Trombe walls.

Vents, fans, and insulation are three Trombe-wall components that have significant effects on efficiency. These components should be used carefully to avoid reverse flow. A fan is a useful appliance that improves the efficiency of the vented Trombe wall by up to 8%. Moreover, size, thickness, colour, wall materials, coating materials, and glazing specifications contribute to the efficiency of Trombe walls. The size of Trombe walls is related to (α), the ratio of the Trombe wall's area to the area of a room's other walls. The optimal size is (α)=37%. The thickness of a mass wall is a parameter that determines the transmission period of stored heat from outside to inside. This parameter varies between climatic regions and should be calculated individually for each installation. However, 30–40 cm mass concrete Trombe walls have performed well in many geographical locations. Dark colours are recommended because they absorb energy much better. Proper insulation of the interior side of the mass wall is strongly recommended to avoid reverse heat transmission. Insulation not only enhances the efficiency of the solar system by up to 56%. It also reduces the size of the mass wall, which leads to lighter buildings.

With regard to wall materials, any material that possesses a high storage capacity can be used in Trombe walls. However, the use of lightweight materials with high storage capacity reduces the size of the mass wall, which structural designers prefer. Coating materials will enhance the wall's performance. However, heat-absorbing film should be designed carefully to avoid overheating. Glazing specifications significantly affect the performance of a solar panel. However, the relationship between glazing specifications and efficiency depends on many variables, including the longitude and latitude of the project. Trombe walls can provide substantial economic benefits, and their advantages outweigh their few negligible disadvantages.

5. Recommendations for further study

For future study, the following recommendations are suggested. The sociological study of the awareness of the benefits of Trombe walls is recommended, particularly among a building's stakeholders. Additionally, research on the preferences of building users in different countries with respect to Trombe walls is suggested. Moreover, studies on the social and cultural impediments, such as aesthetic issues, that discourage individuals from using Trombe walls should be undertaken for different nations.

From the perspective of economics and engineering, research on the optimal thickness of various materials, such as stone, brick, adobe, concrete, etc., for different climatic regions is suggested. Moreover, research on the efficiency of different types of double-glazing arrangements, such as evacuated double-glazing and double-glazing filled with gas or fluid is strongly suggested.

Research on the distance between wall and glazing for different climatic regions is also recommended. Additionally, the importance

of the thickness of the glazing and the effects of glazing thickness on the performance of the Trombe wall should not be overlooked. Moreover, glazing materials should be considered as a new research topic, including means to reduce external reflection, increase the penetration from outside to inside, and reduce heat loss from inside to outside.

Furthermore, comprehensive studies on the effects of mass-wall colour and glazing colour on Trombe-wall performance are recommended.

Research on different absorptive coatings for the solar mass, particularly nanotechnological material, and determining the optimal thickness of coating materials is recommended. Finally, the effect of vent size, i.e., vent height and width, vent-channel geometry, the optimal vent position, optimal fan power and blowing angle are also recommended for future studies. In all suggested research, costs and benefits as well as engineering issues should be considered.

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